University of Glasgow

The Scotland 5G Centre

CSI Communication, Sensing & Imaging

High Frequency Communication Systems

Lecture 9 — Special Lecture

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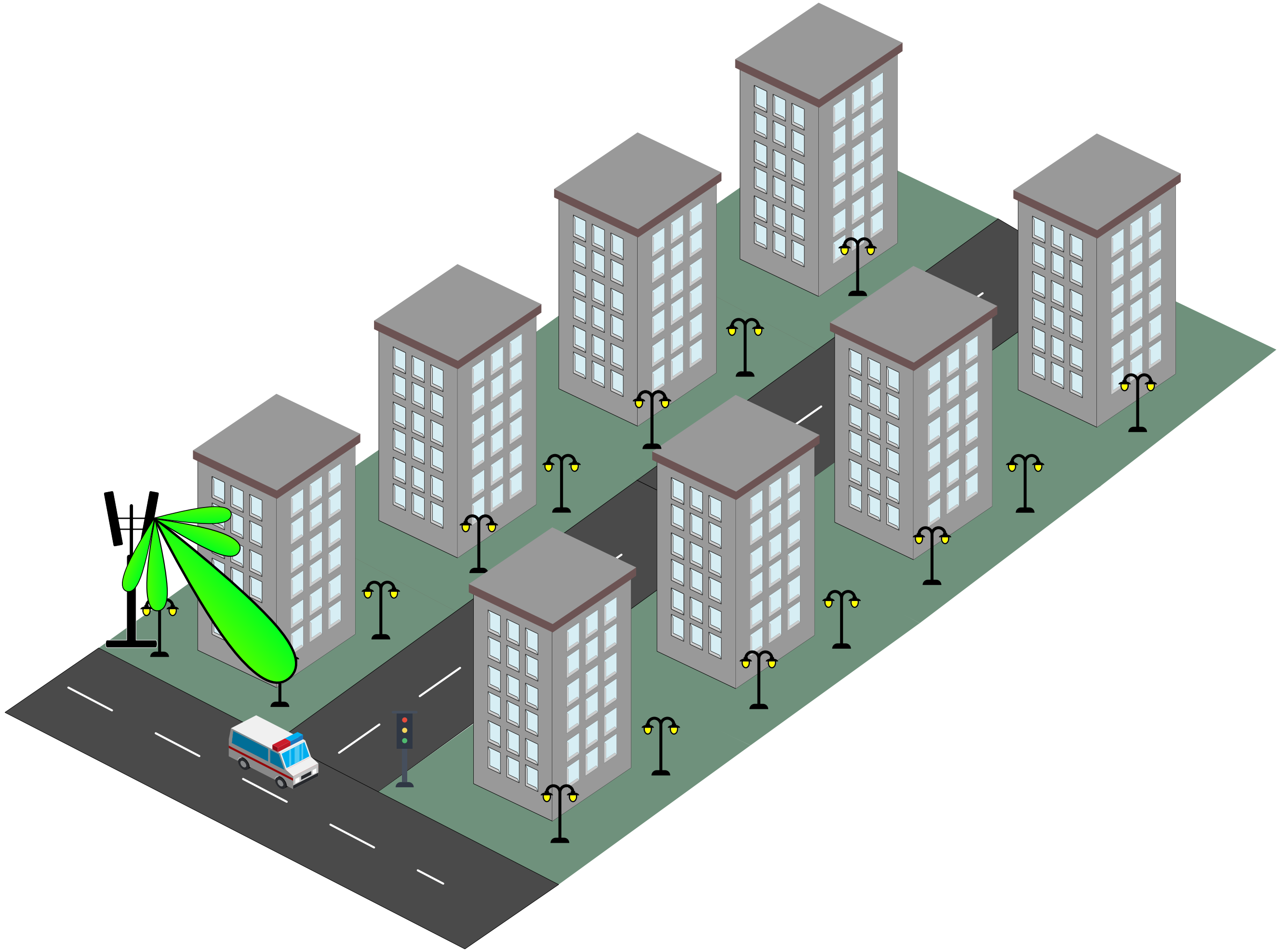
WORLD CHANGERS WELCOME

Lecture Outline

- The wireless channel
  - Modelling the wireless channel
  - Statistical channel models
- Millimetre wave networks
  - Propagation challenges
  - mmWave specific channel characteristics

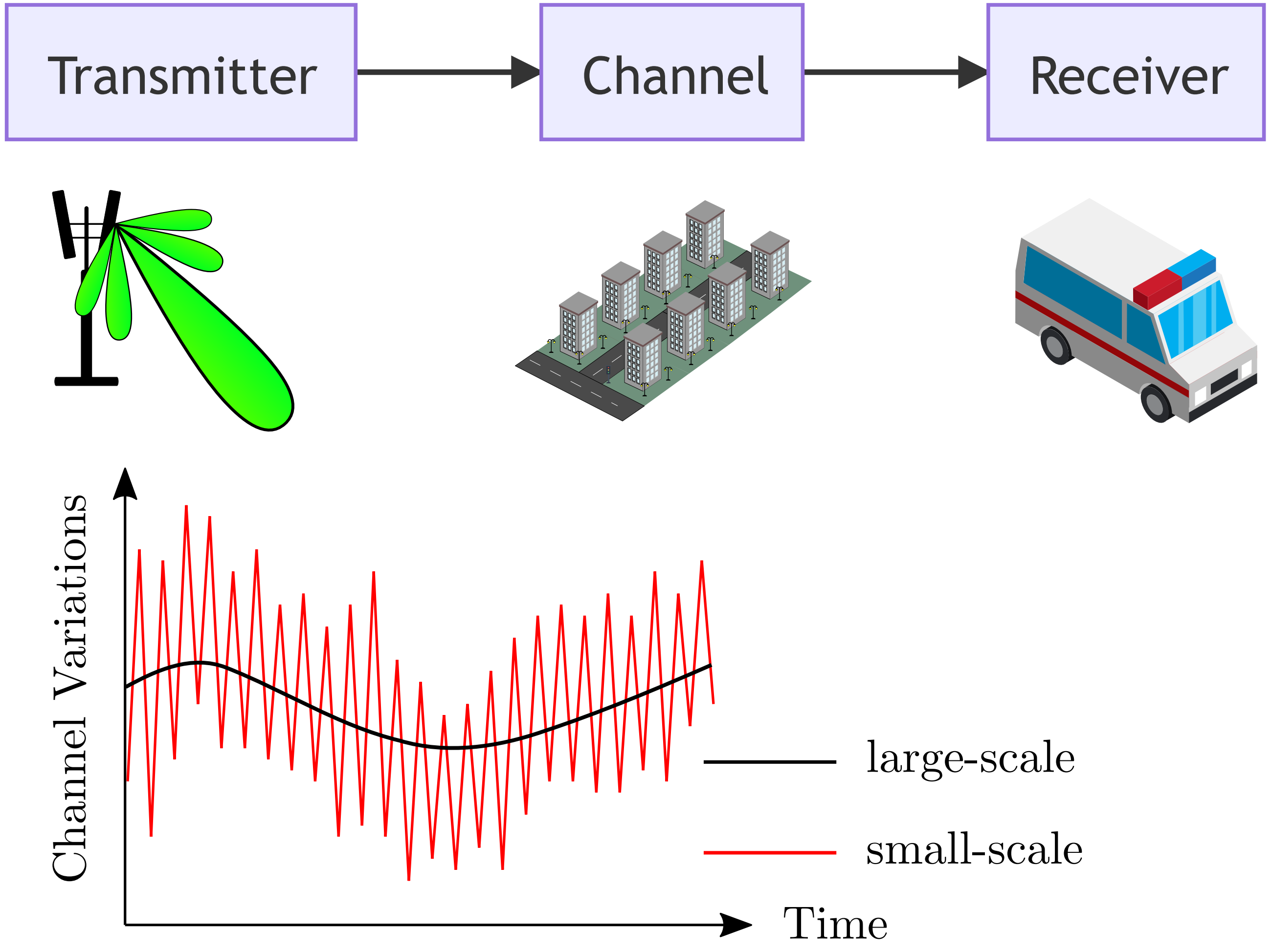
The wireless channel

- Previously we have looked at free-space characteristics of antennas and phased arrays
- In a real world environment, the radiation performance changes due to obstacles such as buildings and roads



The wireless channel

- A wireless channel essentially transfers electromagnetic radiation from the transmitter to receiver
- We aim to model the channel as a system through which the time and frequency variations can be characterised
  - Variations also known as *fading* are either *large-scale* or *small-scale*



Modelling the wireless channel

- To design a communication system, we need to:
  - Determine the location of the base station
  - Determine the power levels of the transmitter
  - Choose the modulation and detection techniques
- Ideally, we would wish to find the above answers by solving the electromagnetic field equations
  - However, in real-world the solutions become increasing complex especially when the mobile user is moving
- Constructing stochastic models of the channel helps us answer some of these questions
  - Provides a sense of what to expect under different scenarios

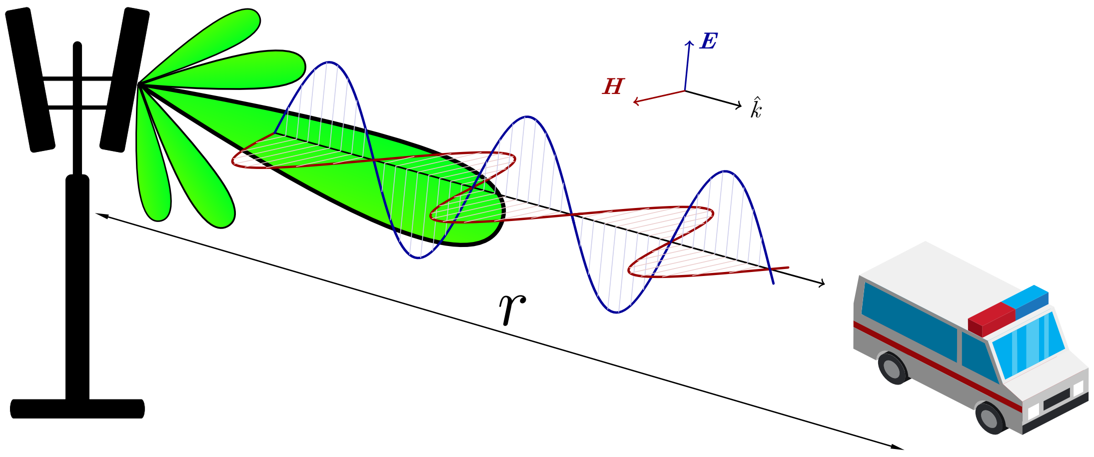
Channel Model - Ideal Scenario 0

- In order to develop the channel model, we start with some overly simplified cases
- Here we look at a free-space scenario with fixed transmit and receive antennas
  - The instantaneous far-field electric field at the receiver for a sinusoidal transmitted signal is:

$$E_{\mathrm{Rx}}(f, t, \mathbf{r}) = \frac{\mathrm{AF}_{\mathrm{Tx}}(\theta, \phi, f)\, \mathrm{AF}_{\mathrm{Rx}}(\theta, \phi, f)\, \cos 2\pi f(t - r/c)}{r}$$

where $\mathbf{r} = P(r, \theta, \phi)$

  - The above relationship is *linear*



Channel Model - Ideal Scenario 1

- For the fixed Tx-Rx case in free-space, we can express the Rx electric field as:

$$H(f) = \frac{\alpha(\theta, \phi, f)\mathrm{e}^{-\mathrm{j}2\pi f r/c}}{r},$$

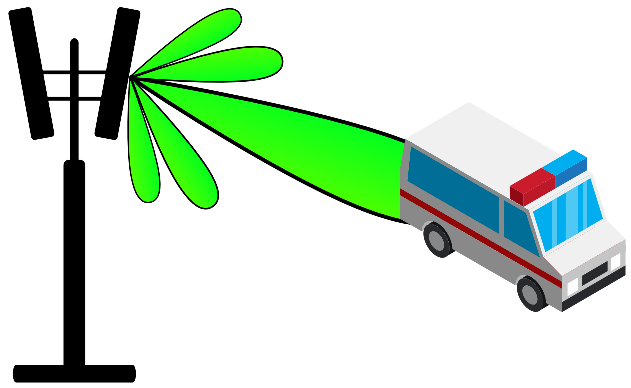
- where $\alpha(\theta, \phi, f) = \mathrm{AF}_{\mathrm{Tx}}(\theta, \phi, f)\,\mathrm{AF}_{\mathrm{Rx}}(\theta, \phi, f)$
- The electric field is simply $\Re\{H(f)\}$

Observation

- $H(f)$ is the system function for an linear, time-invariant (LTI) channel
  - The inverse Fourier transform is the impulse response of $H(f)$
- At any point, the received field is the weighted sum of the transmitted waveforms

Channel Model - Ideal Scenario 2

- Now lets look at a free-space scenario with fixed transmitter but a moving receive antenna
  - The receive antenna is moving with speed v in the direction of increasing distance from the transmitter.
  - The instantaneous position is $\mathbf{u}(t) = (r(t), \theta, \phi)$ where $r(t) = r_0 + vt$
  - The electric field in this case is:
  - $$E_{\text{Rx}}(f, t, \mathbf{u}) = \frac{\alpha(\theta, \phi, f)\,\cos 2\pi f\left(t - (r_0 + vt)/c\right)}{r_0 + vt}$$



Observation

- $H(f)$ for this case is NOT an LTI system due to the Doppler shift
  - The field varies with time as seen by the denominator expression
- This holds true for *relative* motion between the transmitter and receiver.

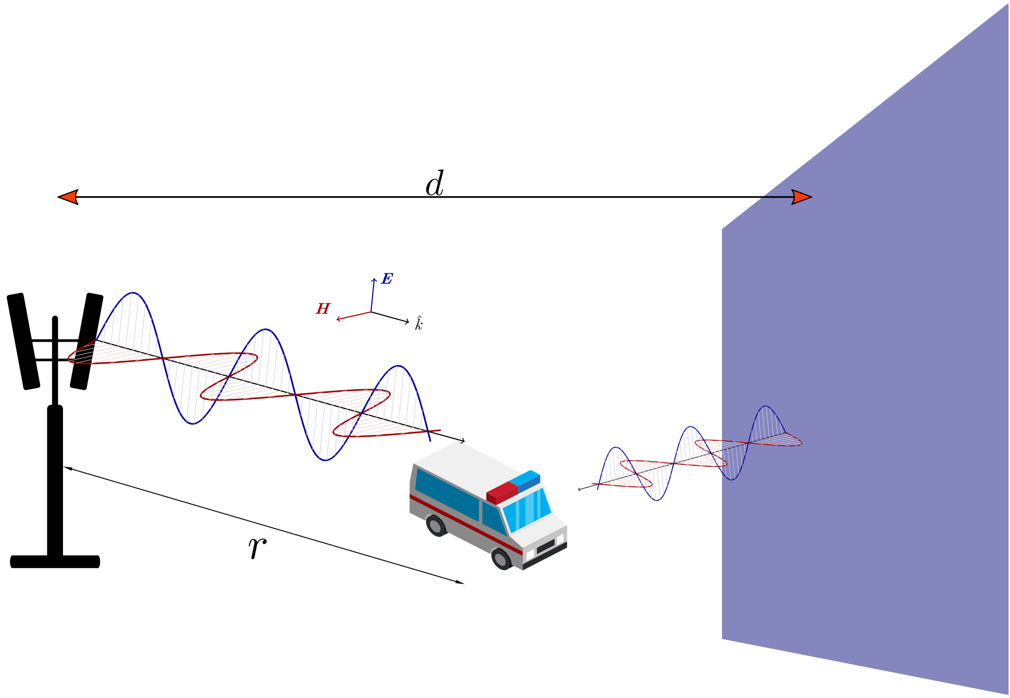
Channel Model - Scenario 3

- Now lets look at a free-space scenario with fixed transmitter and receive antennas and a large perfect electric conductor (PEC) reflecting surface
  - The field solution now consists of a direct and indirect component
  - In this scenario we approximate the fields by *ray tracing*
  - The electric field in this case is:

$$E_{\mathrm{Rx}}(f,t) = \frac{\alpha \cos 2\pi f (t - r/c)}{r} - \frac{\alpha \cos 2\pi f \left(t - (2d - r)/c\right)}{2d - r}$$

- The two components can interfere constructively (*strong signal*) or destructively (*weak signal*), determined by the phase difference:

$$\Delta\theta = \left(\frac{2\pi f(2d - r)}{c} + \pi\right) - \left(\frac{2\pi f r}{c}\right) = \frac{4\pi f}{c}(d - r) + \pi$$



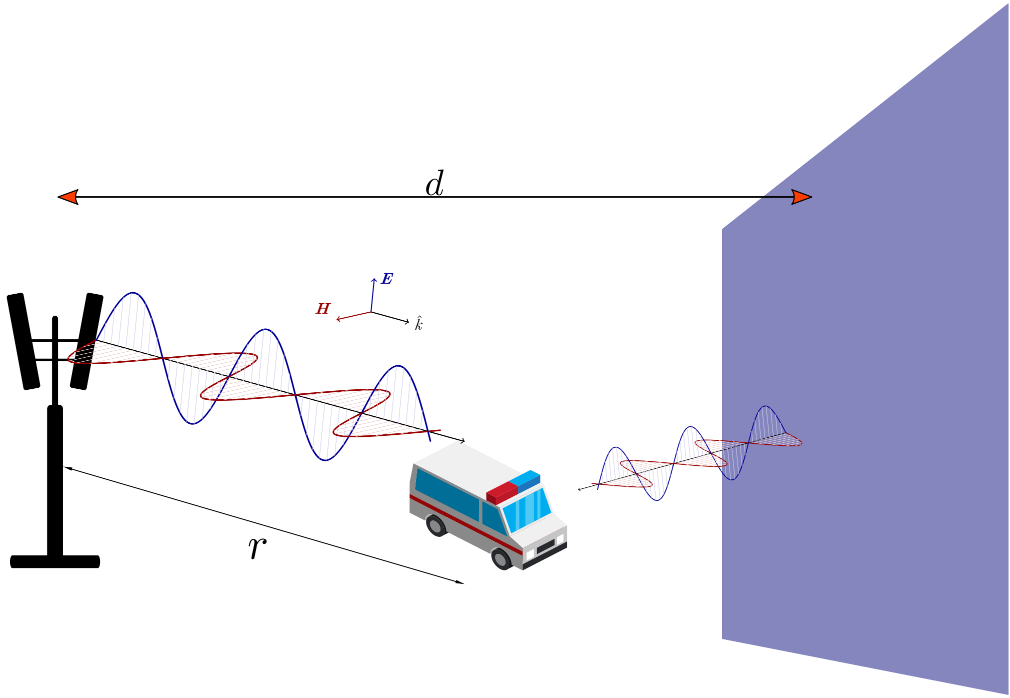
Channel Model - Scenario 3 (contd.)

Observations

$\Delta\theta = \pi \rightarrow$ Destructive Interference

$\Delta\theta = 2\pi \rightarrow$ Constructive Interference

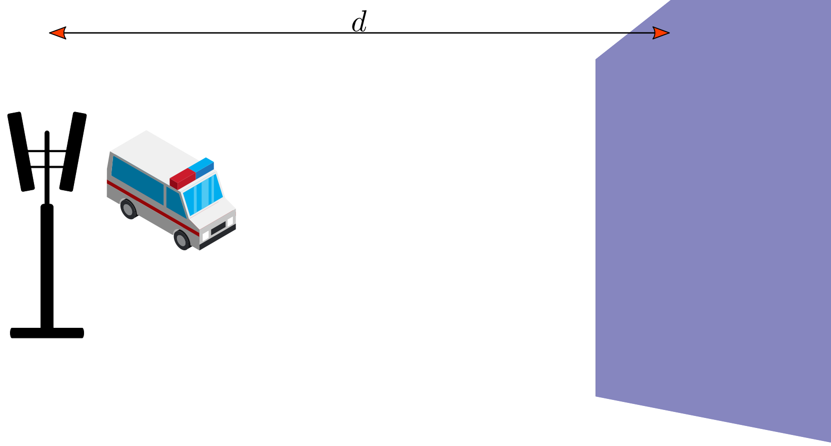
- $\Delta\theta = f(r)$, which means that interference follows a *spatial* pattern
  - For a given frequency, the distance between a peak and a valley is the *coherence distance* $(\lambda/4)$
- $\Delta\theta = f(f)$, implying that two different signals have different propagation lengths and times, resulting in *delay spread*



Channel Model - Scenario 4

- Now a reflecting wall along with a relative motion between transmitter and receive antenna
  - The receive antenna is moving with speed v in the direction of increasing distance from the transmitter.
  - We get a sequence of constructive and destructive interference as the receiver moves; we call this *multi path fading*
  - This movement results in Doppler shifts of the direct and indirect waves
  - Assuming the position to be $\mathbf{u}(t) = (r(t), \theta, \phi)$ where $r(t) = r_0 + vt$
  - The electric field in this case is:

$$E_{\mathrm{Rx}}(f, t, \mathbf{u}) = \frac{\alpha(\theta, \phi, f)\, \cos 2\pi f \left((1 - v/c)t - r_0/c\right)}{r_0 + vt} - \frac{\alpha(\theta, \phi, f)\, \cos 2\pi f \left((1 + v/c)t - (r_0 - 2d)/c\right)}{2d - r_0 - vt}$$



Observation

- The first term experiences a Doppler shift of $-fv/c$ and the second term has fv/c. We call the difference as the Doppler spread
- More importantly, the time variations due to the denominator terms are much slower than the numerator.
  - As an approximation, we ignore the slow variations of the denominator

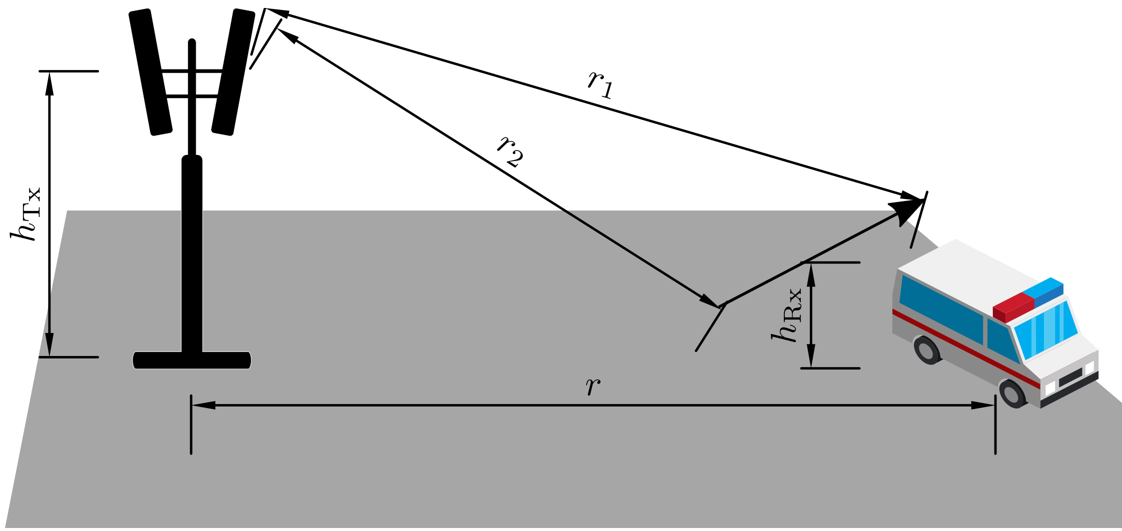
Channel Model - Scenario 5

Reflection from the ground plane

- Typically, $r \gg h_{\text{Tx, Rx}}$, we have an interesting case
- The paths r_1 and r_2 become parallel and the path length difference becomes much smaller than the λ.

Observation

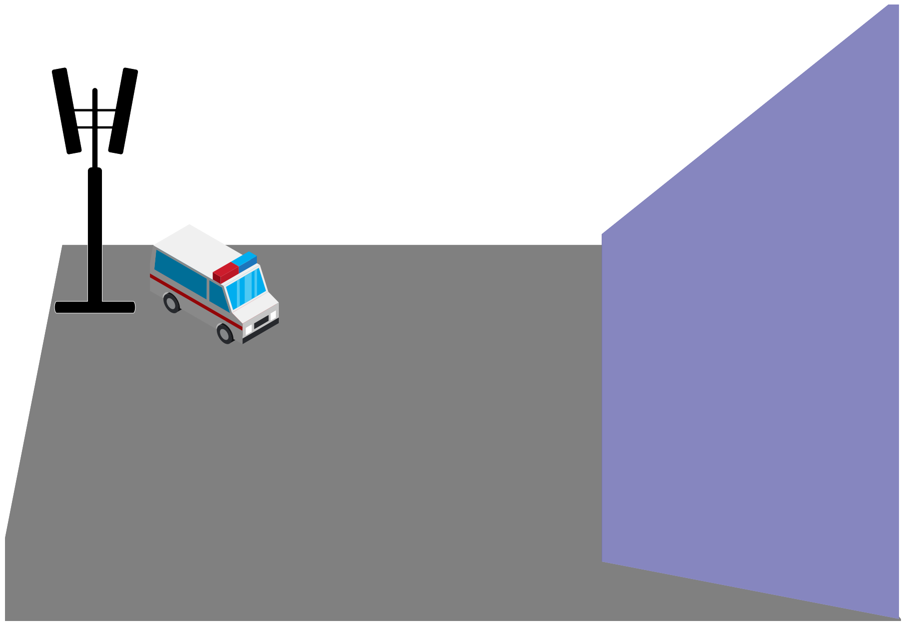
- Due to sign reversal off the ground plane, there is destructive interference
  - The electric field attenuates $\propto 1/r^2$
- For open areas such as countryside, base stations need to be placed accordingly.



Channel Model - Scenario 6

Multiple reflections and moving antenna

- Finding the amplitude and phase of the received signal is no simple task
- We can only rely on ray-tracing simulations for such a scenario
- Another type of reflection, *scattering* occurs from rough surfaces.
  - To model scattering, we divide the surface into infinitesimally small segments and integrate to find the received signal.



Channel Modelling — Observations

- We have seen that the mathematical formulation gets progressively complex as we looked into different scenarios.
- The approach we have taken is *deterministic* where we wish to reproduce the received fields through complex simulations.
- Generally, the system model is *time-variant*
  - However, with the assumption of stationarity (no or relatively small movement within the channel), we get an LTI system
  - In modern mobile networks, we split the channel into different subframes of time (few milliseconds), where stationarity can be assumed

The Wireless Channel - The I/O Model

- From the previous scenarios, the received signal $y(t)$ can be written as:

$$y(t) = \sum_i a_i(t)x\left(t - \tau_i(t)\right)$$

- $a_i(t)$ and $\tau_i(t)$ are the attenuation and the propagation delay for a given path i
- The impulse response $h(t,\tau)$ of the channel is:

$$h(t,\tau) = \sum_i a_i(t)\delta(\tau - \tau_i(t))$$

- The above channel is time-variant as $a = f(t)$
- The frequency response of $h(t,\tau)$ is obtained by taking the Fourier transform:

$$H(f;t) = \int_{-\infty}^{\infty} h(\tau,t)\mathrm{e}^{-\mathrm{j}2\pi f\tau}\mathrm{d}\tau = \sum_i a_i(t)\mathrm{e}^{-\mathrm{j}2\pi f\tau_i(t)}$$

Example - A MIMO Channel

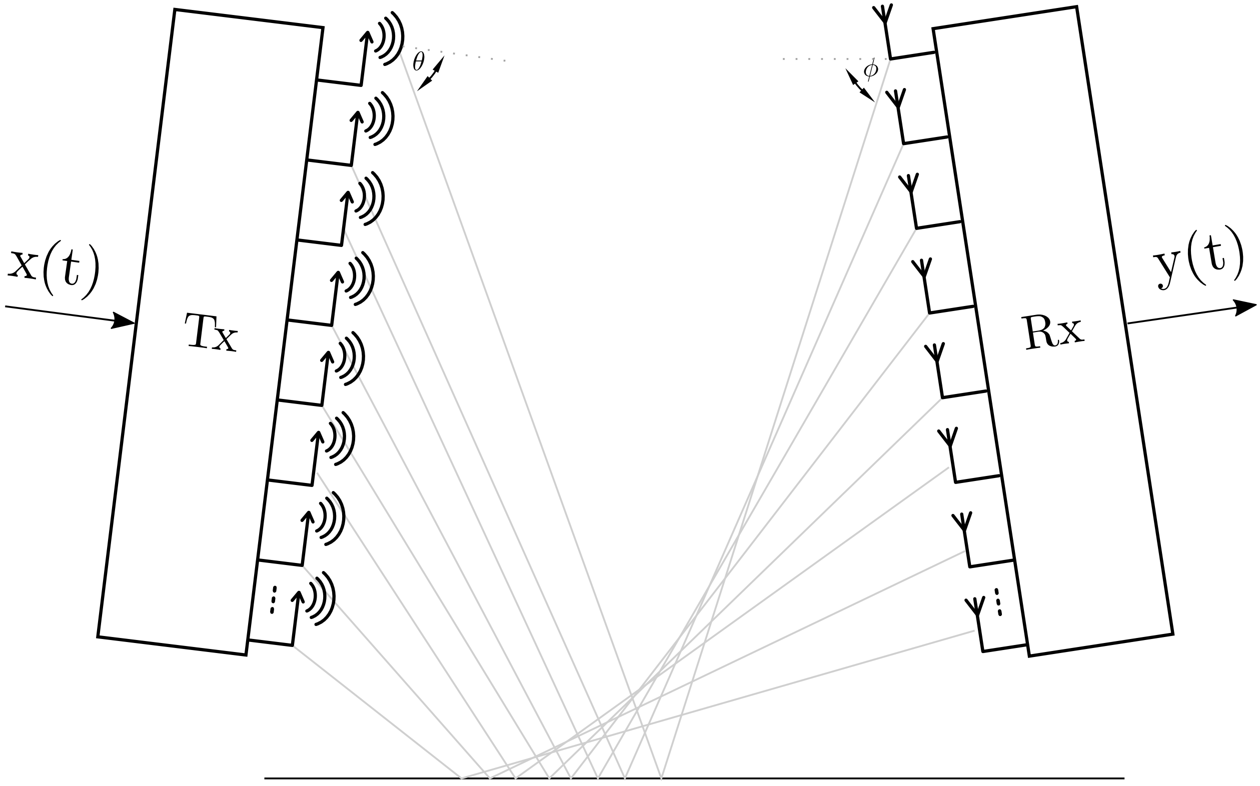
- For a multi-input multi-output (MIMO) system, the channel for a subframe can be expressed as:

$$h_s(\tau) = \sum_{i=1}^{N} a_{i,s}\delta\left(\tau - \tau_i\right)$$

- The attenuation a_i for a given path i contains the Tx and Rx gains, α_{Tx}, α_{Rx} and the reflection/scattering loss α_{path}

$$h_s(\tau) = \sum_{i=1}^{N} \alpha_{\text{Tx},i}(\theta_i)\alpha_{\text{Rx},i}(\phi_i)\alpha_{\text{path},i,s}\delta\left(\tau - \tau_i\right)$$

- Note that the antenna gains remain constant over subframes
- The gain term α_{path} is modelled using a Gauss-Markov process:
- $\alpha_{\text{path},i,s} = \beta\alpha_{\text{path},i,s-1} + \sqrt{1 - |\beta|^2}\nu_{i,s}$
- Here β is an autocorrelation function that is expressed through the famous *Jakes-Clark model*, $\beta = J_0(2\pi T_s f_c v/c)$
- ν is a scaling term modelled as a complex normal random variable $\mathcal{N}(0,\gamma_{i,s})$
  - $\gamma_{i,s}$ is the channel power of a given subframe and path



Example - A MIMO Channel

- Imagine a person walking at $1\,\mathrm{m/s}$ in a sub-6 GHz wireless network
  - Assuming, the subframe time $T_s = 1\,\mathrm{ms}$,
  - $f_c = 1800\,\mathrm{MHz}$,
  - $\beta = J_0(2\pi T_s f_c v/c) = 0.9996$
- This means there is a high correlation between two subframes and the channel effectively remains constant

- Now considering a car moving at $50\,\mathrm{mph}$ which translates to $22.354\,\mathrm{m/s}$
- $\beta = J_0(2\pi T_s f_c v/c) = 0.830$
- As the speed is increased, the correlation decreases, and as a result, the channel changes

Example - A mmWave MIMO Channel

- Repeating the same example for a mmWave network operating at $28\,\mathrm{GHz}$,
  - For a person walking at $1\,\mathrm{m/s}$ the subframe time $T_s = 1\,\mathrm{ms}$,
  - $\beta = J_0(2\pi T_s f_c v/c) = 0.9159$
- With higher frequency, we obtain a reduced correlation compared to before
- Now considering a car moving at $50\,\mathrm{mph}$ which translates to $22.354\,\mathrm{m/s}$
- $\beta = J_0(2\pi T_s f_c v/c) = 0.2153$
- This means the channel changes substantially
  - This is one of the challenges of mmWave communication

Channel Modelling — Observations

- We have seen that the mathematical formulation gets progressively complex as we looked into different scenarios.
- The approach we have taken is *deterministic* where we wish to reproduce the received fields through complex simulations.
- Generally, the system model is *time-variant*
  - However, with the assumption of stationarity (no or relatively small movement within the channel), we get an LTI system

Stochastic Channel Modelling

- Another way to model the wireless channel is the *stochastic* approach
  - Assume the channel response as a stochastic process
  - Tune the properties based on physical considerations
  - This approach is flexible, and adaptable to different physical conditions
  - However, it must be noted that these models carry a high degree of inaccuracy

Modelling Small-scale Fading

The channel impulse response is:

$$\underbrace{\left(\sum_i a_i e^{-j2\pi f_c \tau_i}\right)}_{\text{Gain}=\sqrt{G}\cdot h} \delta(\tau)$$

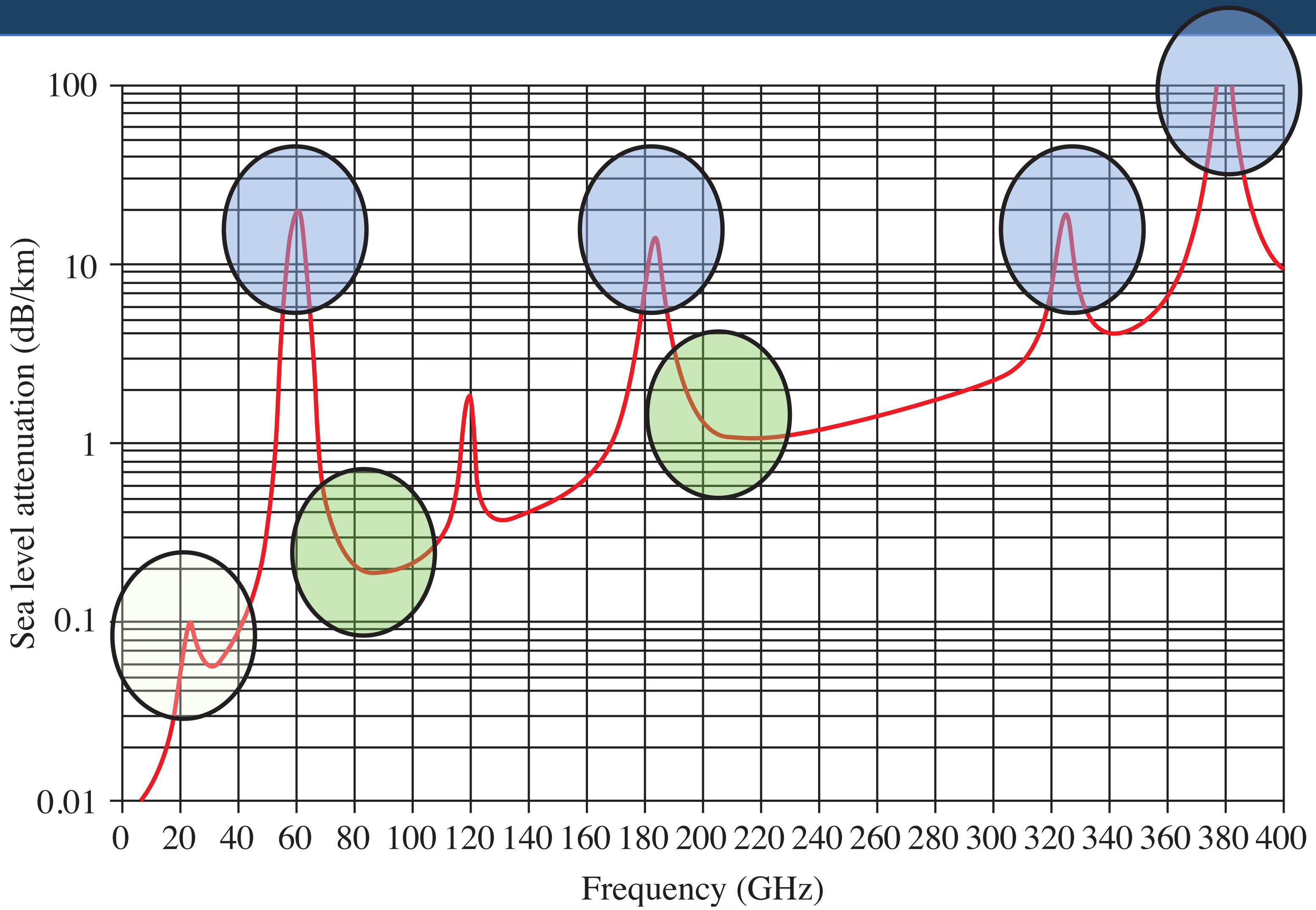
- The received signal is $y(t) = \sqrt{G} \cdot h \times x(t)$
  - The large-scale channel effects are accounted for by $\sqrt{G}$
  - The small-scale effects (instantaneous) are modelled by h normalised to have unit power
  - For a given position and frequency, local effects are modelled as complex Gaussian distribution with zero-mean $h \sim \mathcal{N}_{\mathbb{C}}(0,1)$
  - We use the *Rayleigh distribution* ($f_{|h|}(\xi) = \xi e^{-\frac{1}{2}\xi^2}$) to design the small-scale fading
  - When there is a dominant LOS component, we use the *Rician distribution* ($f_{|h|}(\xi) = 2(\mathrm{K}+1)\xi e^{-(\mathrm{K}+1)\xi^2-\mathrm{K}} I_0(2\sqrt{\mathrm{K}(\mathrm{K}+1)}\xi)$) where $\mathrm{K} = |\mu_h|^2/\sigma_h^2$ is the Rice factor and $I_o(\cdot)$ is the zero-order modified Bessel function of the first kind

Millimetre Wave Networks

- Higher frequency translates to higher bandwidth
- At mmWave frequencies (30 - 300 GHz), the wavelength becomes comparable to the size of a human finger nail
  - This means that the physical environment such as buildings, walls and even us human beings become electrically very large relative to λ.
  - The electromagnetic wave propagation is therefore much more challenging as compared to microwaves (~2.4 GHz)
  - Even the atmosphere acts as a attenuator at higher frequencies

Millimetre Wave Networks

- The green regions suffer from relatively lower atmospheric absorption
  - They can be potentially used for communications
- This is an ideal scenario with other attenuating factors such as rain ignored
  - The figure only considers the absorption due to oxygen molecules in the air



Millimetre wave Challenges

- As studied in the previous lectures, the electric field attenuates as we move away from the source.
  - This is markedly noticeable at mmWave frequencies
- We need highly directional phased array antennas for reliable communications

	$f_c = 460$ MHz	$f_c = 2.4$ GHz	$f_c = 5$ GHz	$f_c = 60$ GHz
$d = 1$ m	-25.7 dB	-40 dB	-46.4 dB	-68 dB
$d = 10$ m	-45.7 dB	-60 dB	-66.4 dB	-88 dB
$d = 100$ m	-65.7 dB	-80 dB	-86.4 dB	-108 dB
$d = 1{,}000$ m	-85.7 dB	-100 dB	-106.4 dB	-128 dB

Free-space path loss at different frequencies

Lecture Summary

- A wireless channel is linear and varies with time
  - With some conditions, we can assume time-invariance which helps in modelling
  - A stochastic approach for channel modelling is flexible
  - Raytracing simulations tools exist that use a deterministic approach
- Millimetre wave communication suffers from various challenges
  - Chief among them is short-range
  - Requires a dominant line-of-sight path for efficient communication

Further Reading

- Wireless Channel Modelling
  - Chapter 2
    - Tse, D., Viswanath, P. (2005). *Fundamentals of wireless communication*. United Kingdom: Cambridge University Press. (Available in Files section)

- Millimetre wave specific channel modelling
  - Chapter 3
    - Rappaport, T. S., Heath, R. W., Murdock, J. N., Daniels, R. C. (2014). *Millimeter Wave Wireless Communications*. (n.p.): Pearson Education.